

# Terrestrial Planet Formation in the Inclined Systems: Application to OGLE-2006-BLG-109L System

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## ABSTRACT

In this work, we extensively investigate the terrestrial planetary formation for the inclined planetary systems (considering the OGLE-2006-BLG-109L system as prototype) in the late stage. In the simulations, we show that the occurrence of terrestrial planets is quite common, in the final assembly stage. Moreover, we find that 40% of the runs finally occupy one planet in the habitable zone (HZ). On the other hand, the numerical results also indicate that the inner region of the planetesimal disk, ranging from  $\sim 0.1$  to  $0.3$  AU, plays an important role in building up terrestrial planets. By examining all simulations, we note that the survivals are located either between  $0.1\sim 1.0$  AU or beyond  $7$  AU, or at the  $1:1$  mean motion resonance of OGLE-2006-BLG-109Lb at  $\sim 2.20$  AU. The outcomes suggest that it may exist moderate possibility for the inclined systems to harbor terrestrial planets, even planets in the HZs.

**Key words:** planets and satellites: formation - star: individual: OGLE-2006-BLG-109L.

## 1 INTRODUCTION

To date, over 500 exoplanets have been discovered (<http://exoplanet.eu>), revealing a diversity of planetary systems. One fascinating fact that has revealed so far is the population of "Hot Jupiters" – gas giants moving in very small orbits (periods  $< 8$  days) about their parent stars, of which the prototype was the first exoplanet discovered, 51 Peg (Mayor & Queloz 1995). Recently, improvement of measurement precisions for both Doppler and transit discovery techniques have made the detection of more than a dozen exoplanets in the mass range from  $\sim 2$  to  $15 M_{\oplus}$  (super-Earths), among which there are also some short-period hot super-Earths – Gl 876 d (Rivera et al. 2005), Gl 581 e (Mayor et al. 2009), CoRoT-7b (Leger et al. 2009) and the Kepler-11 system (Lissauer et al. 2011), etc. These exciting observations greatly motivate us to explore the open issues, to understand the formation and evolution of planetary system.

According to core-accretion model, it is generally believed that planetary formation could be divided into several stages. The starting planetary formation scenario is the agglomeration of  $\mu\text{m}$  dust grains to produce kilometer-sized bodies called planetesimals (Safronov 1969; Wetherill 1980), however, the buildup of particles from cm to meter size is still unclear (Lissauer 1993; Youdin & Shu 2002). After

they emerge, numerous planetesimals can further form 1000-kilometer-sized planetary embryos (protoplanet) and even the cores of gas-giants via direct collision-merger process. In this stage, a few larger bodies would grow rapidly considering their dominant role of gravitational focusing in the runaway growth (Safronov 1969; Wetherill & Stewart 1989). At the time that they are separated into various feeding zones, the largest bodies become massive enough to stir up the nearby small objects, and subsequently the oligarchic growth takes over. In the oligarchic stage, the largest bodies accrete surrounding masses in the disk much slower than they do in runaway growth, but still grow more quickly than those minor bodies (Kokubo & Ida 1998; Goldreich et al. 2004). However, the oligarchic growth may cease once these massive bodies accrete to have their isolation masses, where  $M_{iso} \propto M_{*}^{-1/2} \Sigma_p^{3/2} a^3$  (Armitage 2007), and  $M_{*}$  is the mass of the central star,  $\Sigma_p$ , the surface density, and  $a$ , the semi-major axis. This leads to the formation of larger solid cores for jovian planets at distant orbits. Once they reach critical mass ( $\sim 10 M_{\oplus}$ ), the solid cores begin to accrete gas very fast, and then to grow into giant planets (Kokubo & Ida 2002; Ida & Lin 2004). All aforementioned scenarios are now considered to be completed within  $5 - 10$  Myr, which is critical for the buildup of gas-giants, as inferred lifetimes of gaseous disks (Haisch et al. 2001; Wyatt 2008).

The following stage is featured by terrestrial planet formation under the interference of gas-giants, which is considered to be the longest evolution history with collisional

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coagulation. In this late stage, the formed gas-giants, accompanied with a large number of planetesimals and planetary embryos, have ceased migration since most of gas in the disk disappears. These low-mass objects, under the perturbation of jovian planets as well as their mutual gravitational interaction, may experience a turbulent evolution process that may last for hundreds of million years. During this stage, the embryos are greatly stirred to have crossing orbits, which bring about numerous giant impacts (Chambers & Wetherill 1998). Finally, small bodies are left over after the former stages have been cleaned up and several terrestrial planets emerge (Chambers 2001; Raymond et al. 2004; Zhang & Ji 2009) in the system.

Under some circumstances, the formed planets could be evolved into a highly-inclined configuration, rather than a planar disk perpendicular to the stellar spin axis, which seems quite natural since both the star and planets obtain their angular momenta from the disk. One mechanism that could increase the planetary inclination is the scenario of planet-planet scattering. Chatterjee et al. (2008) show that after strong planet-planet gravitational scattering, the planetary inclination, in the initial range from  $0^\circ \sim 4^\circ$ , could be dramatically excited. In their simulations, more than half of the final configurations have a relative inclination exceeding  $20^\circ$  and nearly a quarter above  $40^\circ$ . Considering the tidal damping timescale for inclination is usually much larger than the star's age (Winn et al. 2005), such highly-inclined planets could be found in the planetary systems which have undergone severe gravitational scattering in their lifetimes.

An alternate scenario for the origin of highly-inclined planets is that they exist in binary systems. The presence of a companion star can affect the orbits of planets and the stability of the planetary system. In tight binaries, a close encounter between a planet and the companion can eject the planet out of the system (Holman & Wiegert 1999). While in wider binaries, secular effects like Kozai resonance become more important. The Kozai mechanism was first introduced to analyze how the orbits of inclined asteroids were influenced by Jupiter (Kozai 1962). Now it is widely accepted to explain the formation mechanism of a relative highly-inclined configuration, such as a Jupiter-size exoplanet in wide inclined binaries (Innanen et al 1997), etc. The Kozai mechanism is only notable when the inclination between the orbits of the planet and the companion,  $i_0$ , is greater than a critical inclination  $i_c$  of around  $40^\circ$  (depending on the system) (Thomas & Morbidelli 1996). If this is the case, the inclination of the planet will oscillate, between  $i_c$  and  $i_0$ , and is coupled to eccentricity  $e$  through the Kozai constant (Thomas & Morbidelli 1996)

$$H_K = \sqrt{a(1-e^2)} \cos i \quad (1)$$

Takeda et al. (2008) showed that the interplay between secular perturbations from a stellar companion and the gravitational coupling planets could trigger the chaotic growth of mutual inclination angles between initially coplanar planets.

Observations have revealed that some planetary systems have large obliquities. Recently, direct measurements of the planets  $\nu$  Andromedae ( $\nu$  And) c and d unveil a  $30^\circ$  mutual inclination angle between them (McArthur et al. 2010). Barnes et al. (2010) showed that planet-planet scattering is a plausible mechanism to explain the observed orbits of  $\nu$  And c and d, though it is unsure whether the scattering

was caused by instabilities among the planets or by perturbations from a nearby low-mass star  $\nu$  And B. In recent years, transit observations have measured  $\lambda \sin i$  for a couple of systems, where  $\lambda$  is the angle between the stellar rotation axis and the orbital angular momentum of a transiting planet, indicating that some systems with large  $\lambda$  of  $30^\circ \pm 21^\circ$  for TrES-1b (Narita et al. 2007), and  $62^\circ \pm 25^\circ$  for HD 17156b (Narita et al. 2008). Such planetary systems might have a chaotic dynamical history that produce the present highly-inclined planets (Chatterjee et al. 2008). Currently, it is hard to determine the proportion of the exoplanet population with a significant inclination, which requires precise measurements of  $\lambda$  for a large quantity of the systems. However, in this sense, it is extremely significant for one to make a deeper understanding of complicated building process for planetary formation, by investigating the configuration of highly-inclined planets.

In this work, we extensively perform a series of groups of simulations, to explore the planetary formation in the late stage for the inclined system (application to OGLE-2006-BLG-109L, see Table 1 for details), by considering major factors that might have influence on final assembly of terrestrial planets. The paper is structured as follows: §2 describes numerical setup for investigation. §3 presents the results and the discussion is given in section §4. Finally, we briefly summarize the main outcomes in §5.

## 2 NUMERICAL SETUP

In our simulations, the initial conditions emulate the environment at the beginning of the chaotic phase of terrestrial planet formation (Chambers 2001; Raymond et al. 2004, 2006), Moon-sized planetesimals and Mars-sized planetary embryos are distributed in the disk, in company with the OGLE-2006-BLG-109Lb,c analogues. The orbital elements are adopted from the observation data (Gaudi et al. 2008). For each run, we assume the initial objects to follow a distribution with orbital radius as  $N \propto r^{-1/2}$ , corresponding to the annular mass in a disk with surface density (Weidenschilling 1977),

$$\Sigma \propto r^{-3/2} \quad (2)$$

The Hill radius  $R_H$  within which the gravity of planet dominates is,

$$R_H = (M_p/3M_*)^{1/3} a \quad (3)$$

where  $M_p$  and  $M_*$  are the masses of planet and central star respectively. Then the feeding zone of a planet at a given position  $a$  can be expressed as,

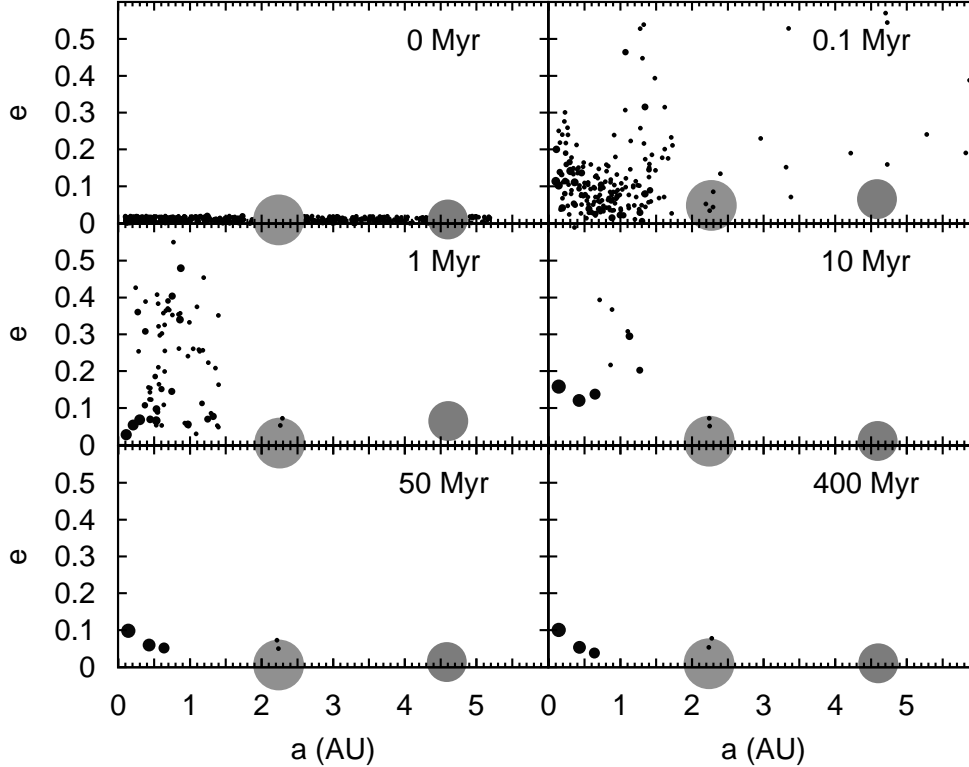
$$F_a = C R_H \quad (4)$$

where  $C$  is a constant. As the size of a planet grows, the corresponding feeding zone expands as well. Nevertheless, we could obtain the isolation mass of planet at a given orbital position by accumulating the total mass of the materials in the feeding zone of the original disk,

$$M_{\text{iso}} = 2\pi a \cdot 2F_a \cdot \Sigma_p = 4\pi a \cdot C \left( \frac{M_{\text{iso}}}{3M_*} \right)^{1/3} a \cdot \Sigma_p \quad (5)$$

which gives,

$$M_{\text{iso}} \propto a^2 \cdot M_*^{1/3} \cdot \Sigma_p \propto a^{3/4} \quad (6)$$



**Figure 1.** Snapshots of a run in the simulation of Group 1. The panels show the eccentricity versus semi-major axis for each surviving body at  $t = 0, 0.1, 1.0, 10, 50$ , and  $400$  Myr. The radii of each object are related to their masses, with radius  $\propto m^{1/3}$ . Two giants are, respectively, at  $2.3$  and  $4.6$  AU. Three terrestrial planets have formed at  $\sim 10$  Myr and remain stable over  $\sim 400$  Myr.

**Table 1.** Orbital parameters of two gas-giants (Gaudi et al. 2008).

Planet	a (AU)	e	Mass ( $M_{Jup}$ )
OGLE-2006-BLG-109L b	2.3	0.001	0.71
OGLE-2006-BLG-109L c	4.6	0.11	0.27

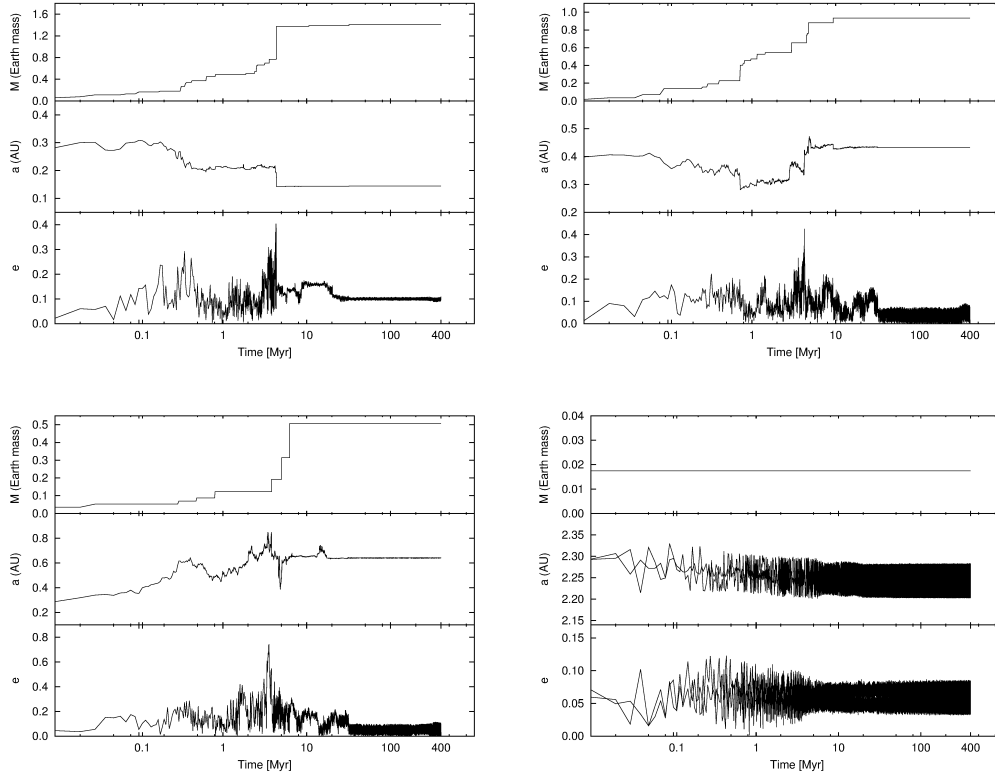
Therefore, we set the masses of planetary embryos and planetesimals following the relationship  $M_{embryo} \propto a^{3/4}$ , proportional to the total mass in the embryo's feeding zone (Raymond et al. 2004). On the other hand, all the planetesimals in our simulations were set with an equal mass of  $0.017 M_{\oplus}$ .

The initial orbital elements of each embryo and planetesimal were randomly generated: argument of pericentre, longitude of the ascending node, and mean anomaly of each small object were randomly set between  $0^\circ$  to  $360^\circ$ ; the eccentricities range from 0 to 0.02, while the inclination vary from  $0^\circ$  to  $1^\circ$ . For giant planets, to investigate terrestrial planetary formation in an inclined configuration, the inclination of the outer giant planet changes for each group but that of the inner gas-giant remains, in the meantime all other orbital data keep unchanged in the each initial run.

**Table 2.** Simulation details of each group.

Number	Embryos	Planetesimals	Total Mass ( $M_{\oplus}$ )
Group 1	30	470	10
Group 2	30	470	10
Group 3	50	950	15
Group 4	30	470	10
Group 5	30	470	10

As mentioned, one of the main goals of this work is to explore terrestrial planet formation in the late stage under the circumstance of highly-inclined planetary system, where the mutual inclination of the outer giant planet is taken into account. Consequently, we carried out five groups of simulations, containing 46 runs in total. The major difference between each group is the distribution range of the initial bodies. In all groups, two giant planets were set to emulate the OGLE-06-109L system in each run, with initial orbital parameters  $(M_P, a, e_P) = (0.71 M_{Jup}, 2.3 \text{ AU}, 0.001)$  and  $(0.27 M_{Jup}, 4.6 \text{ AU}, 0.11)$  (Gaudi et al. 2008), as shown in Table 1. We adopt the stellar mass as  $0.5 M_{\odot}$  (Gaudi et al. 2008), and assume its radius to be  $\sim 0.8 R_{\odot}$ . For each group, the simply difference between individual runs is the inclination of the outer giant, OGLE-2006-BLG-109Lc. Some de-



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**Figure 2.** Mass, semi-major axis, and eccentricity versus time of all the survivals in the run in Figure 1. Three terrestrial planets formed at  $\sim 10$  Myr and remain in stable orbits afterwards. Note that two planetesimals survive at the 1:1 MMR with respect to OGLE-2006-BLG-109b, as shown in the right bottom panel.

tails of each group are listed in Table 2, which is also summarized as follows,

- **Group 1** - 5 runs. In each run, embryos and planetesimals were distributed in the range  $0.1 \text{ AU} < a < 5.2 \text{ AU}$ . The inclination of OGLE-2006-BLG-109Lc in each run is adopted from  $0^\circ$  to  $40^\circ$ , in increments of  $10^\circ$ .
- **Group 2** - 14 runs. In each run, embryos and planetesimals were in the range  $0.3 \text{ AU} < a < 5.2 \text{ AU}$ . The inclination of OGLE-2006-BLG-109Lc in each run is from  $0^\circ$  to  $10^\circ$  in increments of  $1^\circ$ , and from  $10^\circ$  to  $40^\circ$  in increments of  $10^\circ$ .
- **Group 3** - 17 runs. In each run, embryos and planetesimals were in the range  $0.3 \text{ AU} < a < 5.2 \text{ AU}$ . The inclination of OGLE-2006-BLG-109Lc in each run is from  $0^\circ$  to  $10^\circ$  in increments of  $1^\circ$ , and from  $10^\circ$  to  $40^\circ$  in increments of  $5^\circ$ .
- **Group 4** - 5 runs. In each run, embryos and planetesimals were distributed in the range  $0.1 \text{ AU} < a < 10 \text{ AU}$ . The inclination of the outer giants in each run is from  $0^\circ$  to  $40^\circ$ , in increments of  $10^\circ$ .
- **Group 5** - 5 runs. In each run, embryos and planetesimals were distributed in the range  $0.3 \text{ AU} < a < 10 \text{ AU}$ . The inclination of the outer giants in each run is from  $0^\circ$  to  $40^\circ$ , in increments of  $10^\circ$ .

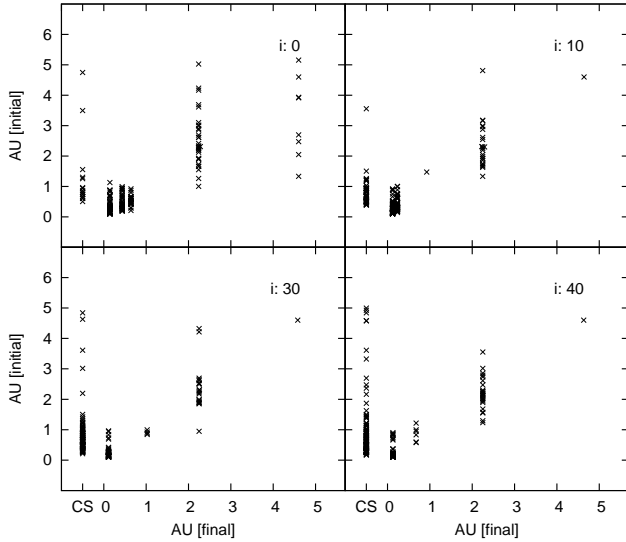
Both embryos and planetesimals were considered to gravitationally interact with each other in our simulations. Objects were allowed to collide, and we assume that they merge into a single body with no fragmentation after a collision. All 46 runs were performed using a hybrid symplectic

algorithm provided by the MERCURY integration package (Chambers 1999). Each run evolved for 400 Myr, with a time step length no more than 3.0 days ( $\sim$  a twentieth of a period for the body at 0.3 AU). The Bulirsch-Stoer tolerance for all runs is of  $10^{-12}$ . In most of the simulations, energy is conserved to better than 1 part in  $10^{-3}$ , and the angular momenta conserved in  $10^{-11}$ . Next, we will briefly introduce simulation outcomes.

### 3 RESULTS

From the simulations, we can note that a typical accretion scenario occurs in the late stage planet formation (Chambers 2001; Ji et al. 2011). In the beginning, the planetary embryos and planetesimals are quickly excited to highly-eccentric orbits due to dramatic perturbations arising from OGLE-2006-BLG-109Lb,c. Subsequently, frequent orbital crossings emerge when the objects approach each other, which may result in violent collisions amongst planetesimals and embryos. Herein a large portion of the runs show that the planetesimal disk becomes quite turbulent within 1 Myr, while in some cases their chaotic period of movement could last a little longer, and most of the initial objects were removed by ejections or collisions.

Fig. 1 illustrates that six snapshots of one run in Group 1. The figure shows that three terrestrial planets emerged at  $\sim 10$  Myr and their orbits kept stable over subsequent evo-

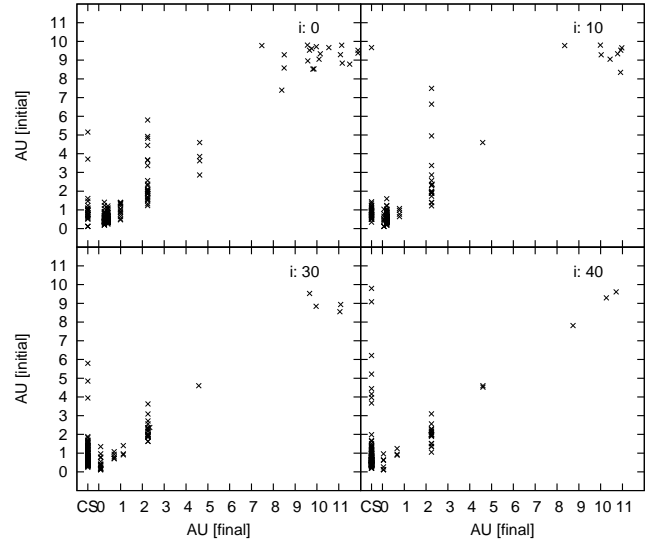


**Figure 3.** Trace of the destination of all objects from 4 runs in Group 1. Each panel presents original versus final semi-major axes for all objects – except those scattered out of the system ( $a > 100$  AU) – of which the mutual inclination for the giants are, respectively,  $0^\circ$ ,  $10^\circ$ ,  $30^\circ$ , and  $40^\circ$ . The vertical axis indicates the original semi-major axis of each body, while the horizontal axis indicates the final value (CS denote the central star).

lution. Moreover, at the end of this run, there are also two survivals locked in the 1:1 Mean Motion Resonance (MMR) with OGLE-2006-BLG-109Lb, which reminds us of the Trojan/Greek population of asteroids at triangular points for Jupiter. In our simulations, survived Trojans are not rare to find, for they are simply unaccreted planetesimals.

The dynamical evolution process within 10 Myr for the bodies plays a key role in creating members at final configurations. As shown in Fig. 2, it represents the mass, semi-major axis, and eccentricity versus time for all final bodies. We observe that three terrestrial planets had finally made to reach about Earth-size mass in the stage. The eccentricities of each body change violently during this chaotic stage, then they were damped down to  $\leq 0.1$ . In the final, the orbits of three terrestrial planets remained stable afterwards. However, two planetesimals were trapped into 1:1 MMR with OGLE-2006-BLG-109b, and their orbital parameters are nearly unchanged over the timescale of 400 Myr.

To summarize all outcomes, we note that the terrestrial planet formation is very common in the simulation, as a great number of runs may remain two or more planets eventually. In addition, over 2/3 of the runs have 1-3 survival planetesimals at the 1:1 MMR with respect to OGLE-2006-BLG-109Lb. In the cases of the initial embryos and planetesimals extending 10 AU, the planetary accretion in the outer disk may still work. In such cases, a significant portion of objects could stay at the region 7-15 AU in the end.



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**Figure 4.** Trace of the destination of the objects from 4 runs in Group 4 —layout is the same as for Figure 3. In these runs, there are also some planetesimals survived in the outer planetesimals disk.

### 3.1 Dependence on the outer highly-inclined giant

With an increasing mutual inclination between two giants, a great many of smaller planetesimals either scattered out of the system, or had been directly engulfed by the central star. Therefore a few number of objects were left in the planetary disk, leading to the difficult of making terrestrial planets. Table 3 presents the statistic results over the simulations of Group 3, in which each run has an initial population of 1000 bodies. The table summarizes the number of scattered bodies, those hit into giants and host star, the remaining mass and the accretion rate. For a moderate mutual inclination ( $i_m$ ) of  $\sim 10^\circ$  to  $25^\circ$ , the population of ejected bodies could be much more than that of  $i_m < 5^\circ$ . For a higher  $i_m (> 25^\circ)$ , the number of ejected objects decreases. In this sense, a large relative inclination of two giants seems to be less effective in throwing out the embryos or planetesimals. However, on the other hand, in the highly-inclined configurations the population that hit into the central star could be significantly enhanced. As shown in Table 3, with  $i_m < 10^\circ$ , simply a small number of planetesimals, say 20 - 40 objects, entered into the central star; while for a larger mutual inclination, the number could rise nearly linearly. Moreover, in the case of  $i_m = 30^\circ, 40^\circ$ , the bodies that originally lie in the outer disk might run into the central star over shorter timescale. In a word, the relatively inclined orbital configuration do play a significant role in the formation of terrestrial planets, inferring that the lower mutual inclination of two giants, the more effective for planetary accretion.

Fig. 3 shows the destination of the initial objects in simulation of Group 1, except those were driven out of the systems. The vertical axis indicates the original semi-major axis of each body, while the horizontal line means the final.

**Table 3.** Statistic results for the simulations Group 3. The columns are, respectively, the mutual inclination, the number of ejected bodies, the objects collided with giant planets and central star, the remaining mass (in Earth-mass) and the surviving mass fraction for each run.

Inclination ( $^{\circ}$ )	Ejection	Giants	Star	Remaining Mass ( $M_{\oplus}$ )	Surviving Mass Fraction
0	626	69	20	3.404	23%
1	669	43	26	3.360	22%
2	665	54	23	3.450	23%
3	664	48	20	3.122	21%
4	668	37	24	3.526	23%
5	686	46	28	2.954	20%
6	705	49	30	2.701	18%
7	707	39	28	3.230	21%
8	725	40	39	2.121	14%
9	690	53	37	2.460	16%
10	748	43	31	1.954	13%
15	743	43	53	1.491	10%
20	746	47	76	0.6314	4%
25	752	50	89	0.6184	4%
30	711	57	107	0.1441	1%
35	699	61	105	0.02275	0%
40	685	63	120	0.01137	0%

The figure shows that along with the augment of the mutual inclination of two jovian planets, the number of bodies that hit into the central star may increase notably. Especially, one may notice that the situation is more apparent in the inner planetesimal disk at 0.1 - 1.5 AU. Furthermore, Fig. 3 shows that in the case of  $i_m = 30^{\circ}, 40^{\circ}$ , a large proportion of the objects in the inner disk could finally rush into the host star, leading to few residuals in the disk for further planetary accretion. This trend is in a good agreement with those as shown in Table 3 for Group 3. Again, Fig. 4 shows the destination of initial objects in Group 4, which reveals a similar trend like Fig. 3. A large number of bodies that finally run into the central star, may cause the deficiency in mass for the inner disk to produce more terrestrial planets, and a scarcity of survivals in the outer disk.

As mentioned previously, a great many of bodies had been either driven out of the system, or collided with the giant planets or central star for inclined configuration, leading to the difficulty in planetary accretion. Moreover, Fig. 5 shows the remaining bodies for each run from Group 3 over 400 Myr, except for  $i_m = 35^{\circ}, 40^{\circ}$  where no terrestrial planet formed. The figure clearly reveals that the mass of created planets decreases as the mutual inclination grows. As shown in Fig. 5, the  $i_m = 30^{\circ}$  run illustrates that a terrestrial planet with mass of  $\sim 0.1M_{\oplus}$  was finally formed at  $\sim 0.8$  AU, indicative of inefficiency for planetary accretion. To sum up, simulation results demonstrate that terrestrial planetary formation is extremely related to the mutual inclined configuration of the giant planets in the system.

### 3.2 Dependence on the orbital distribution of initial bodies

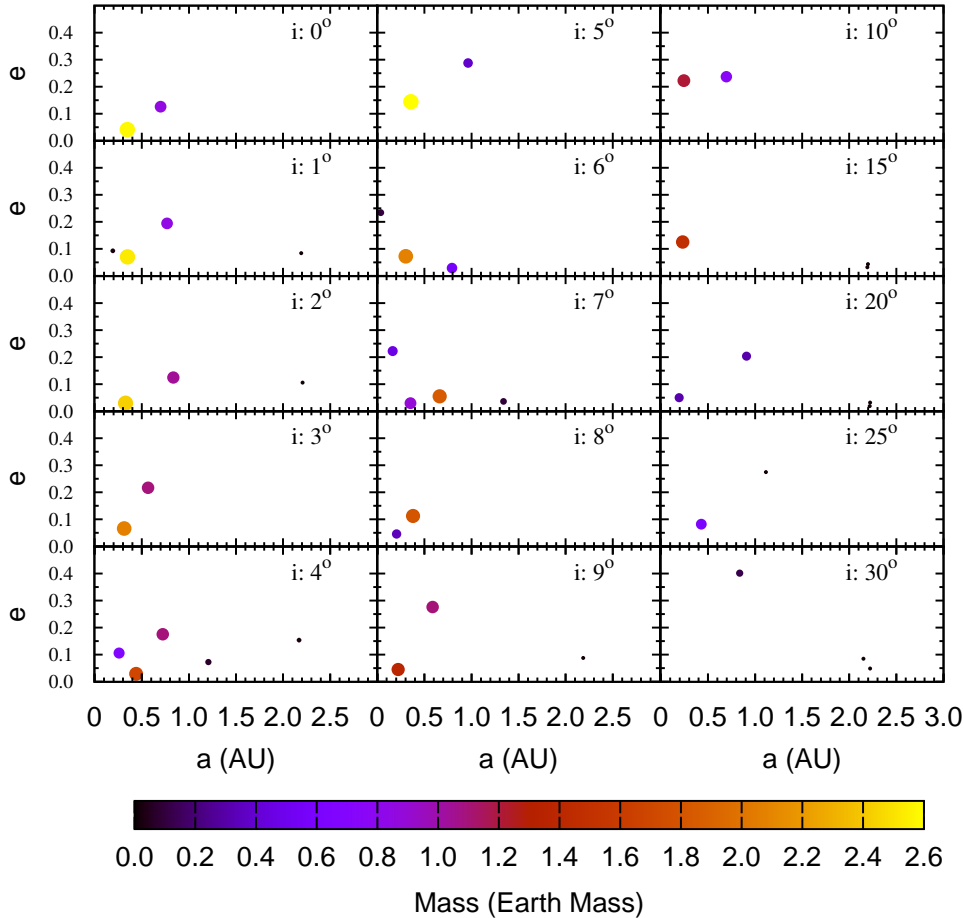
The different distribution ranges of initial bodies also play a major part in yielding final members in the system for each simulation. Table 4 introduces five contrast groups, and in each run the number of the initial bodies is 500, with a total mass of  $10 M_{\oplus}$ , but they are distributed in various initial orbits. As shown in Table 4, in each group – in which all runs

have equal mutual inclination relative to giant planets – runs with an initial disk of an inner edge at 0.1 AU seem to have advantage of occupying more survivals of terrestrial planets and planetesimals, with a larger total mass of remaining bodies and efficient accretion rate of the terrestrial planets.

Fig. 6 shows the outcomes of ten runs from Group 1 and 2, to compare the overall results for different initial distribution ranges. Similar to Table 4, both the number and mass of formed terrestrial planets in Group 1 ( $0.1 \text{ AU} < a < 5.2 \text{ AU}$ ) is larger than those in Group 2 ( $0.3 \text{ AU} < a < 5.2 \text{ AU}$ ). Considering the smaller semi-major axis of two giants in this system, planetary embryos and planetesimals in the outer region of the planetesimals disk would suffer severe gravitational influence from two giant planets; hence, the planetesimals, locating at  $1 \sim 7$  AU could not remain stable under dramatic perturbation from them. The only exception is the 1:1 MMR region with respect to the OGLE-2006-BLG-109b, while no such Trojan was found for the outer giant planet. This may explain an almost empty disk for all final configurations, ranging from  $1 \sim 7$  AU, in our simulations. On the contrary, the inner part of the disk is strongly favor of producing terrestrial planets, because of the relatively higher density of the population and stronger influence of the central star. In this sense, these cause the inner region of the planetary disk, from 0.1 to 0.3 AU, to be very important for planetary accretion for terrestrial planets.

The above feature is also reported in much wider distribution cases, where the embryos and planetesimals originally located at an outer edge of disk, extending to 10 AU. Figure 7 shows the terrestrial planetary accretion becomes more difficult when the mutual inclination of the gas-giants increases. One may note that in the final evolution there exist several survivals in the outer region of the disk up to 7 AU. In Figure 8, the runs of  $0.1 \sim 10$  AU configuration would relatively have less and smaller final planets than those in the  $0.3 \sim 10$  AU cases.

In addition, in the cases of initial distribution up to 10 AU, there also exist several survivals in the outer realm of the planetary disk at 7 AU. Some survivals experienced sev-



**Figure 5.** All the final configurations of the runs that have terrestrial planets formed in Group 3. The panels show the eccentricity versus semi-major axis for each surviving body at the end of each run. The radii and colors of each object are related to their masses, with radius  $\propto m^{1/3}$ . The mutual inclination of the two giants is labeled in each panel. Note that the mass of formed planets decreases as the mutual inclination between the giants increases.

eral accretion, at a limited rate, in comparison with those in the inner disk; others, like Mar-sized protoplanets, emerged around the region of  $7.5 \sim 11$  AU in the end of simulations. Compared with our solar system, these formed bodies may be in a rescaled position of Uranus, Neptune and the Kuiper belt objects, implying that Neptunian-mass planet may be formed if more bodies were initially placed there and abundant mass were considered over much longer timescale evolution.

### 3.3 Planetary formation in the habitable zone

As mentioned, the OGLE-2006-BLG-109L was the first double planet system, discovered by gravitational microlensing method (Gaudi et al. 2008). Two companions occupy the masses of  $\sim 0.71$  and  $\sim 0.27M_J$ , respectively, and each orbits its central star at about 2.3 and 4.6 AU. The mass of the star is  $\sim 0.5 M_\odot$ , and this system is resemblance to a rescaled solar system, for the mass ratio and the separation between them is comparable to those of Jupiter and Saturn. The habitable zone around a star is defined as the region

where a terrestrial planet with  $N_2$ - $CO_2$ - $H_2O$  atmosphere could maintain liquid oceans on its surface (Kasting et al. 1993). As for this system, the HZ is about  $0.25 \sim 0.36$  AU from the star (Migaszewski et al. 2009). Since the OGLE-2006-BLG-109L planetary system bears very close similarity to solar system, one may wonder to know whether it is possible to harbor other planets, especially for potential Earth-like planets in the HZ. Recently, Malhotra & Minton (2008) analyzed secular dynamics for OGLE-2006-BLG-109L and presented a stable model to explain the existence of two supposed terrestrial planets in the system. Migaszewski et al. (2009) and Wang et al. (2009) further showed that Earth-size bodies might be formed in the HZ of the system.

From our simulations, we note that more than 40% (19 out of 46) of the total runs have formed planets in the HZ, within  $0.25 \sim 0.36$  AU (Migaszewski et al. 2009). In fact, we find that in certain configurations with a smaller mutual  $i$  ( $\leq 10^\circ$ ) may have a great probability, e.g., 16 out of 22 runs formed a terrestrial planet in the HZ. Fig. 9 shows all final configurations of 19 runs have produced habitable planets

**Table 4.** Statistics over 20 selected runs from four different groups, considering the mutual inclinations. The name of each run denotes the initial distribution range and the relative inclination between two giants, e.g., 10-0.1-00 indicates a run for embryos and planetesimals initially ranging from 0.1 to  $\sim 10$  AU, with a  $0^\circ$  mutual inclination for two giant planets. In the following columns, the table lists the final number of remaining terrestrial planets and planetesimals (referred as TP and PL, respectively), the total remaining mass (in Earth-mass) and the surviving mass fraction of formed terrestrial planets.

Simulation	Initial	Final(TP + PL)	Remaining Mass ( $M_\oplus$ )	Surviving Mass Fraction (TP)
10-0.1-00	500	3+23	3.090	27%
10-0.3-00	500	2+13	2.832	27%
5.2-0.1-00	500	3+2	2.852	28%
5.2-0.3-00	500	2+2	1.900	19%
10-0.1-10	500	3+12	2.630	24%
10-0.3-10	500	2+10	1.585	13%
5.2-0.1-10	500	3+2	2.469	24%
5.2-0.3-10	500	2+2	1.604	16%
10-0.1-20	500	3+9	1.946	18%
10-0.3-20	500	1+6	0.777	7%
5.2-0.1-20	500	2+2	1.864	18%
5.2-0.3-20	500	3+1	0.931	9%
10-0.1-30	500	3+8	1.174	11%
10-0.3-30	500	0+8	0.381	3%
5.2-0.1-30	500	2+1	1.334	13%
5.2-0.3-30	500	1+1	0.210	2%
10-0.1-40	500	2+4	0.436	4%
10-0.3-40	500	0+6	0.222	1%
5.2-0.1-40	500	2+0	1.363	14%
5.2-0.3-40	500	1+3	0.229	3%

at the end of numerical simulation, where Run 1  $\sim$  8 are adopted from Group 2, Run 9  $\sim$  16 from Group 3, and Run 17, 18 and 19 from Group 1, 4 and 5, respectively. Obviously, as illustrated in Fig. 9, most of the runs are from Group 2 and 3, which have an initial distribution for embryos and planetesimals ranging from 0.3 - 5.2 AU.

The common feature in these runs is indicative of the final configuration to consist of two terrestrial planets, with one in the HZ and the other in outer region from 0.4 to 1.0 AU. Typically, the planet in the HZ seems to be more massive ( $0.75 \sim 2.6M_\oplus$ ), while the outer body has a smaller mass ( $0.27 \sim 1.81M_\oplus$ ). In addition, there also exists some configurations (totally 6 runs) that three terrestrial planets formed. In these cases, the other two planets do not reside in habitable zone. However, no configuration of a single habitable planet has been found in the final simulations, although it was considered to be a stable model under the combinations of a low eccentric orbit and some proper orbital parameters of jovian planets (Migaszewski et al. 2009).

The uniform characteristics of the formation of habitable terrestrial planets in our simulations over 400 Myr, could be served as a significant evidence of the stability of the HZ in the OGLE-2006-BLG-109L system.

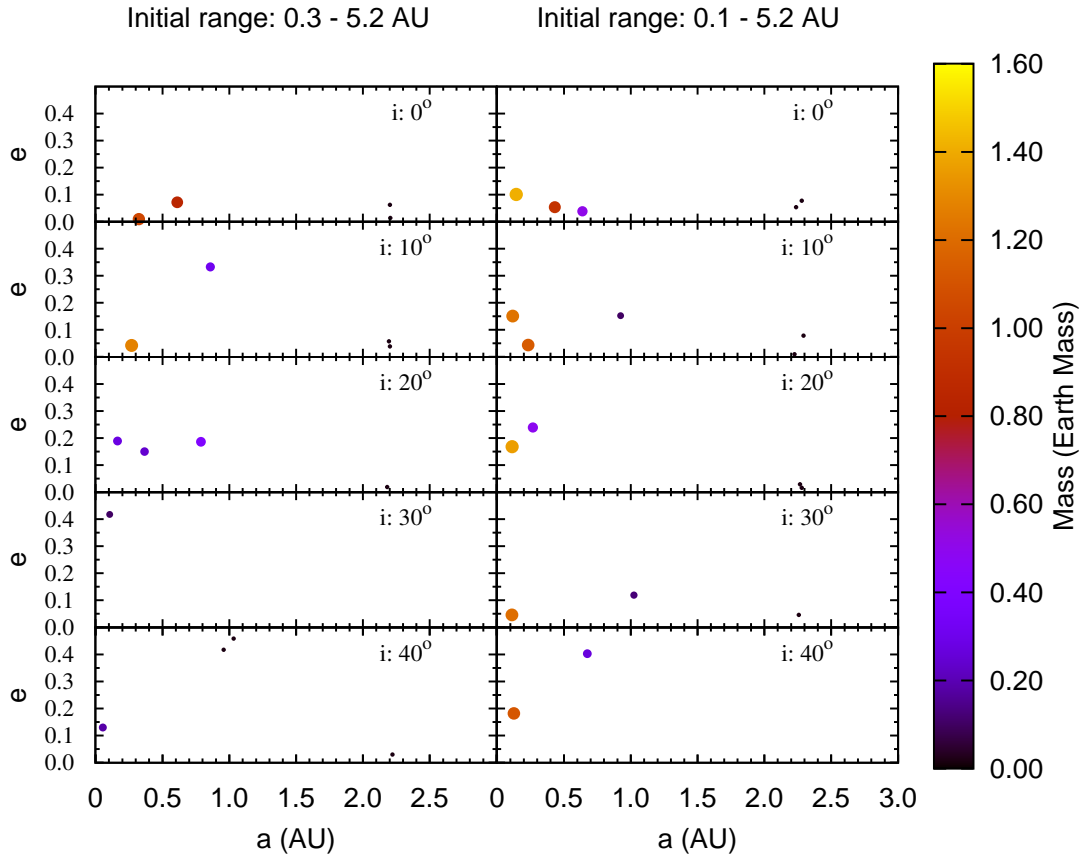
## 4 DISCUSSION

The OGLE-2006-BLG-109L system has drawn many researcher's attention as it is resembling to a rescaled solar system. Wang et al. (2009) showed that the stability of the region is within  $a \leq 1.5$  AU and  $a \geq 9.7$  in their numerical simulations, and also pointed out the HZ is broader

enough for a stable Earth-mass planet. From the runs, we find that terrestrial planets could emerge in the regions where  $0.1 < a < 1.13$  AU or  $a > 7.5$  AU. For  $1.13 < a < 1.5$  AU, there may remain stable for an additional planet as suggested by Wang et al. (2009), where a great many of initial bodies are ejected due to strong stirring of two jovian planets, and they either scatter out of the system or directly run into the central star. As a result, simply a few number of objects were left as accretion stuff for further planetary formation, consequently none of the planets has finally formed in this region. Herein we also confirm the stability of the HZ in this system: 19 out of total 46 runs have a final planet locating in 0.25 to 0.36 AU, which is in good agreement with theirs.

Malhotra & Minton (2008) found that secular resonance arising from the massive planets in the system could drive an Earth-mass planet out of the HZ, and an additional inner planet, with mass larger than  $0.3M_\oplus$  at  $a \leq 0.1$  AU, is required to maintain the habitability of the OGLE-2006-BLG-109L system. Therefore, they suggest a possible configuration with at least two additional planets in order to support a potentially habitable Earth-like planet in this system. However, in the 19 simulations that formed a habitable planet, we show that most of final configurations bear one larger planet ( $0.75 \sim 2.6M_\oplus$ ) in the HZ, and an additional one or two less massive ( $0.27 \sim 1.81M_\oplus$ ) planets in the outer region ranging from 0.4 to 1.0 AU. Simply one run in our work may have a similarity to the configuration as mentioned by Malhotra & Minton (2008), where three planets with parameters  $(M_P, a) = (0.1M_\oplus, 0.0385 \text{ AU})$ ,  $(2.05M_\oplus, 0.3044 \text{ AU})$ , and  $(0.55M_\oplus, 0.7951 \text{ AU})$ . Our numerical results a bit differ from their theoretical analysis





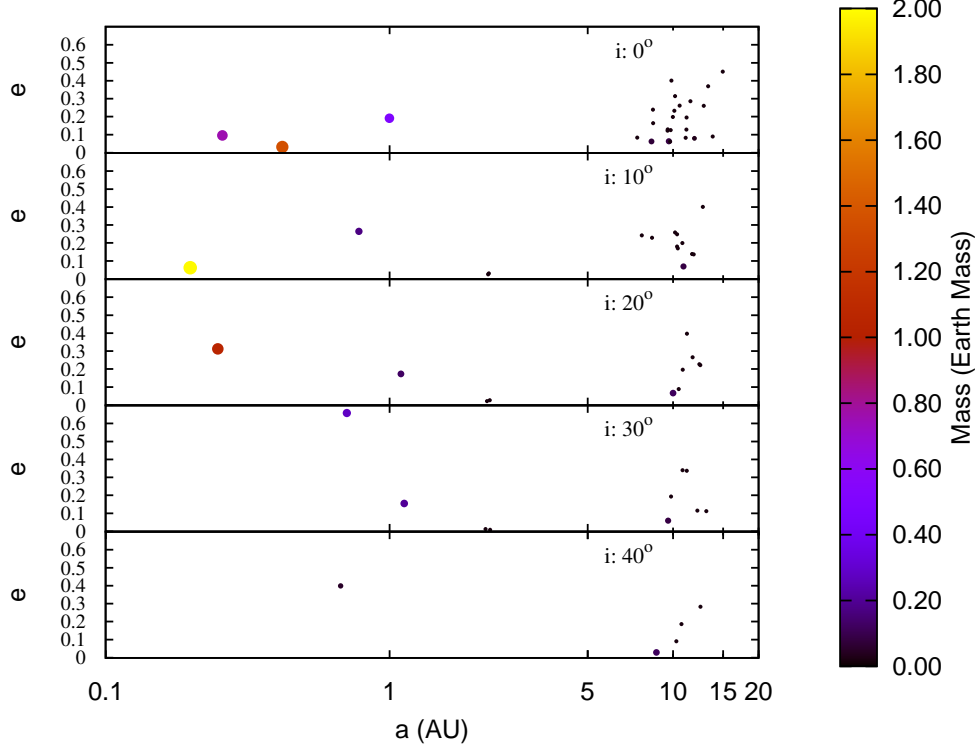
**Figure 6.** The comparison of final configurations of 5 runs in Group 1 (where  $0.1 \text{ AU} < a < 5.2 \text{ AU}$  for initial objects) and Group 2 ( $0.3 \text{ AU} < a < 5.2 \text{ AU}$ ), and the layout is the same as Figure 5. Note that in the case of Group 1 more terrestrial planets could form.

in the initial distribution of inner boundary (where we set to be 0.1 AU) for planetesimals and embryos. However, from viewpoint of habitability, our simulations are in consistent with their suggestion that at least two additional planets are required to support a potentially habitable Earth-like planet in this system.

In the simulations, the configurations with a single stable habitable planet as mentioned by Migaszewski et al. (2009) do not occur, where a terrestrial planet could survive to move on low-eccentric orbit for the combination of the apsidal angle of jovian orbits, eccentricities and semi-major axes consistent with the observations. However, our work differs from those in that in our simulations we adopt the highly-inclined configuration between two jovian planets, and we also have set a much larger total mass and more initial bodies than those of Migaszewski et al. (2009), where they simply considered less bodies - 50 Moon-sized planetary embryos between 0.2 - 2 AU, leading to a great difficulty in producing more terrestrial planets. Nonetheless, our work is in concurrence with their study in the fact that most of the runs formed a habitable planet have an additional body with a similar mass in the region  $0.6 \sim 0.8 \text{ AU}$ .

Recently, Wang & Zhou (2010) investigated the formation of terrestrial planets in the early stage of planet formation at the time the gaseous disk has not dissipated yet. They indicated that the formation and the final mass of the habitable planet in the OGLE-06-10L system depends on the stellar accretion rate  $\dot{M}$ , which means the rate at which the star accretes gas from the disk, and the speed of Type I migration, which is more significant. In this work, we take into account formation of terrestrial planets in the late stage after the gas disk has dissipated. We concentrate on the various distribution range of the initial bodies and mutual inclination between two gas giants. Generally, the higher relative inclination, the harder the planetary accretion. This is because the relative highly-inclined outer planet may disturb the embryos and planetesimals in a more effective manner, which results in a large number of objects thrown out of the system or run into the central star, and then a limited number of bodies are left in the disk for further planetary accretion.

With a relatively higher inclination, a large amount of the bodies would be excited to be swallowed by the central star, especially those in the inner region 0.1 to 1.5 AU. More-



**Figure 7.** Final configurations of 5 runs in Group 4. The layout is the same as Figure 5, but the horizontal line is in a logarithmic scale. The figure shows the terrestrial planetary accretion becomes difficult in the case of the increasing mutual inclination of the gas-giants. In the final, there exist several survivals in the outer region of the disk extending to 7 AU.

over, the total mass of the scattered bodies also increases as the mutual inclination does. In a word, the above-mentioned two factors do no good to form terrestrial planets for the highly-inclined configurations.

Given two giants in this system with close-in orbits, the embryos and planetesimals in the inner disk were under strong gravitational influence arising from the jovian planets. Our results show that the total accretion mass in the runs of the initial distribution at 0.1 AU is much larger than those distributed at 0.3 AU. In this sense, it may imply that the location of the inner planetesimal disk, as well as the number of the initial bodies, plays an important part in the planetary accretion. On the other hand, embryos and planetesimals between 1 ~ 7 AU could not survive so long owing to dramatic stirring of two gas-giants, except those at 1:1 MMR location with the inner planet, which reminds us Trojan/Greek Group of Jupiter. In two groups, the accretion does still work in the outer region beyond 7 AU, with a moderate rate and limited speed. Figs. 7 and 8 show that several Mars-sized protoplanets emerge between 7.5 to 11 AU over 400 Myr. In addition, there are also many survival planetesimals at 7 ~ 16 AU. Suppose a larger number and a longer integration time were chosen at the beginning of these runs, it may assume that Neptune-like planets might appear in

the end due to further planetary accretion in the outer disk, similar to the outer structure of our solar system.

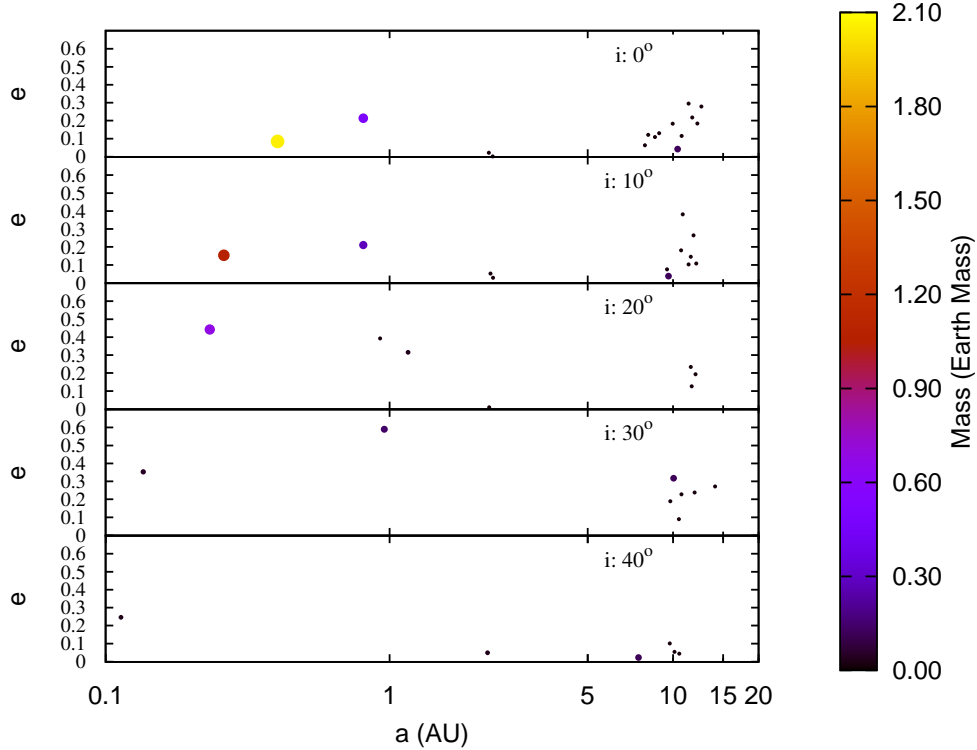
## 5 SUMMARY

In this work, we have carried out several groups of simulations, with 46 runs in total, to investigate the planet formation in the late stage for the OGLE-2006-BLG-109L system. We may summarize the main results as follows:

Firstly, the simulation outcomes show that it is quite common for terrestrial planet or possible habitable planets to finally form residing in 0.25 ~ 0.36 AU. In addition, our work may imply that the OGLE-2006-BLG-109L system bears a great probability of harboring one or additional terrestrial planets.

Secondly, the comparison of results for different groups suggests that the efficiency of planetary accretion may decrease as the relative inclination of two giant planets increases.

Finally, our results further show that embryos and planetesimals in the 0.1 - 0.3 AU may play an important role in planetary accretion. Moreover, we find that the bodies initially locate in the ~ 1.1 AU - 7 AU of planetary disk are



**Figure 8.** All the final configurations of 5 runs in Group 4, the layout is the same as Figure 7. In Comparison with Figure 7, the runs of 0.1 ~ 10 AU configuration would relatively have less and smaller final planets than in the 0.3 ~ 10 AU distribution cases.

mostly unstable over the dynamical evolution, which leads to no survivals for embryo or planetesimal at this range in all simulations, except those at  $\sim 2.2$  AU close to 1:1 MMR with OGLE-2006-BLG-109Lb. On the other hand, the planetary accretion could continue to happen but keep a much slower pace in the outer planetary disk for those runs with initial semi-major axes extending 10 AU, where a significant number of residuals eventually remain in the system in the simulations.

Currently, the Kepler mission is surveying 156,000 faint stars for transiting planets as small as Earth, e.g., Kepler-9 (Holman et al. 2010) and Kepler-11 (Lissauer et al. 2011). Our results here imply the great probability to occupy stable terrestrial planets in the OGLE-2006-BLG-109L system, which should be carefully examined by forthcoming observations. With the help of high precision of ground-based and spaceborne measurements on the exoplanets, we might expect the discovery of solar system analogues in the near future.

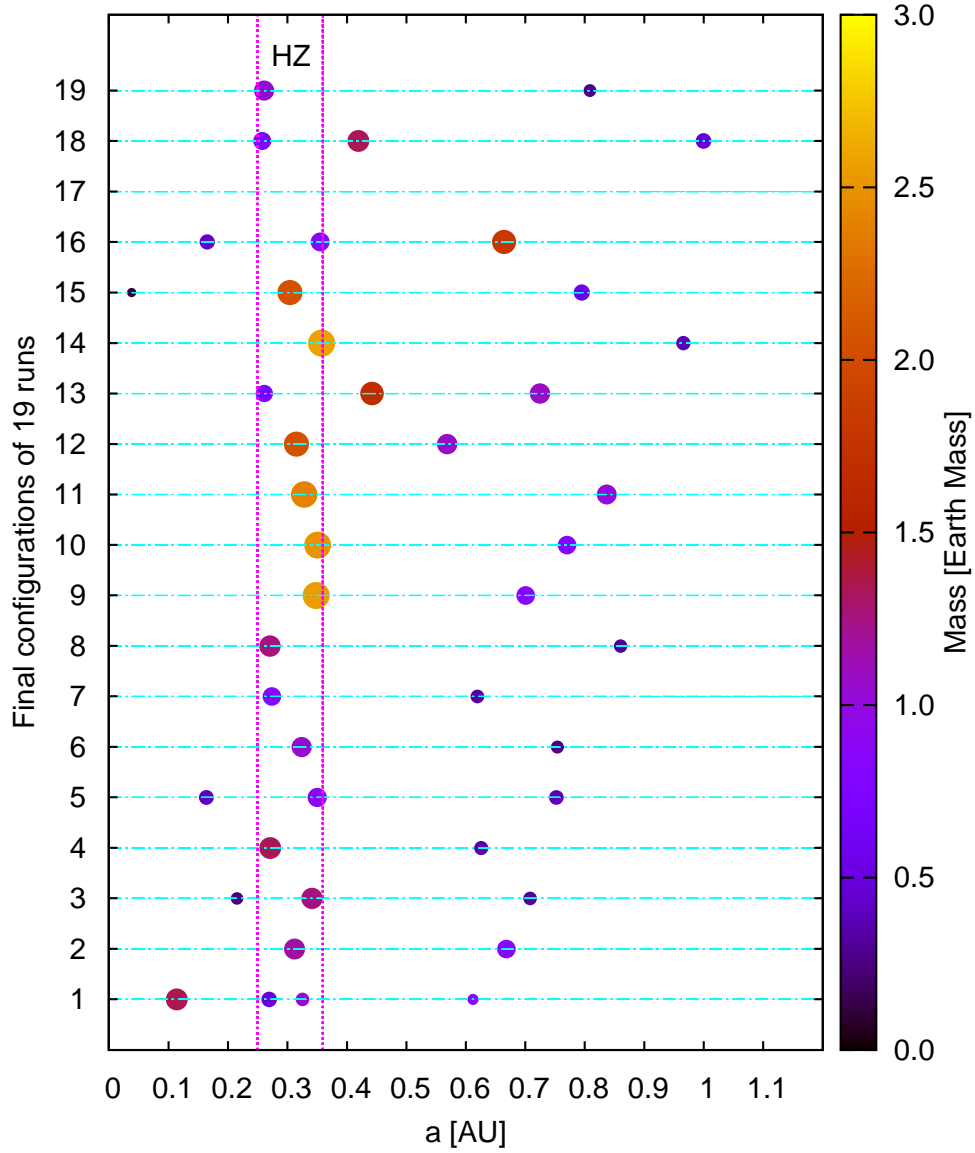
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**Figure 9.** Final configurations of 19 runs that have formed habitable planets. The vertical axis indicates the number of each run. The radii and colors of each object are related to their masses, with  $\text{radius} \propto m^{1/3}$ . Two vertical dotted lines represent the inner and outer boundaries of the HZ for this system. The figure also shows that in the final runs for two terrestrial planets, one resides in the HZ and the other locates in outer regime ranging from 0.4 to 1.0 AU.

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